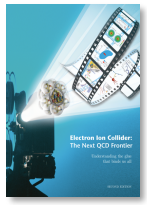
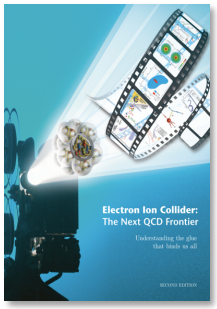
Center for Frontiers in Nuclear Science

"Science: Compelling & fundamental, Realization: Timely"

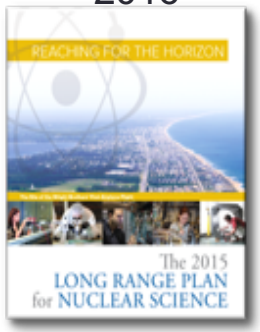


Electron Ion Collider & its relevance to Snowmass 2021

2015

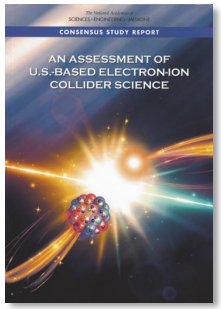


2016



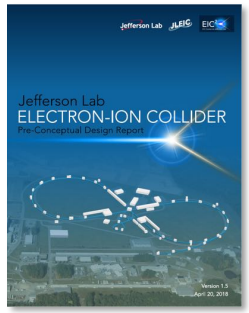
Physics of EIC

2018

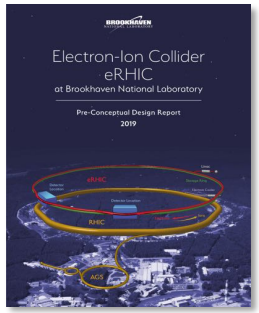


Evaluation

2019



2019 - future



Realization

Stony Brook University

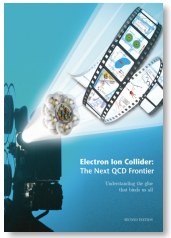
Abhay Deshpande

BROOKHAVEN NATIONAL LABORATORY

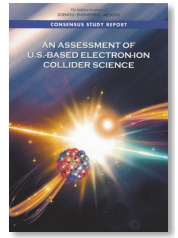
Today on the agenda:

- Introduction to the Electron Ion Collider
- The science of the Electron Ion Collider ➔ the science that convinced the Nuclear Science community & the National Academy of Science, Engineering & Medicine
- Synergies: Opportunity for the HEP community➔ Studies through Snowmass 2021
- EIC Users Group's current activity: Yellow Report Writing for a Conceptual Design Report March 2021; to feed into the Technical Design of a detector by 2023.

The Electron Ion Collider



The EIC design parameters



Requirements for the US electron ion collider (EIC) were defined by a community led White Paper (1212.1701.v3). The EIC with those parameters was endorsed by the Nuclear Science Advisory Committee (NSAC) in 2015/6 & by the National Academy in its evaluation of EIC science in 2018.

- High luminosity: 10^{33}-10^{34} $cm^{-2}sec^{-1}$ a factor 100-1000 times HERA (@DESY)
- Broad range in center-of-mass energy: 20 – 140 GeV
- Polarized beams e-, p, D, ^{3}He… C, Be with flexible spin patterns & spin orientation
- Wide range in hadron species: protons…. Uranium
- Up to two well-integrated detector(s) into the machine lattice for max. acceptance

EIC Status & Evolution

- CD0 : December 19, 2019
- Site BNL : January 9, 2020
- BNL and JLab realize EIC as partners

- A formal EIC project is now setup at BNL
- BNL+Jlab management & scientists are working together to realize it on a fast timeline.

- CD1 anticipated March 2021
- CD2 September 2022 (final design)
- CD3 4th Quarter FY2023 (start construction)

- EIC Early Finish 4th Q FY2029
- EIC CD4 4th Q FY 2030


SCIENCE & INNOVATION ENERGY ECONOMY SECURITY & SAFETY SAVE

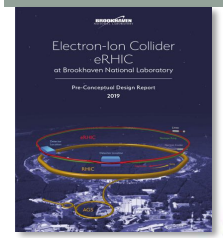
Department of Energy

U.S. Department of Energy Selects
rookhaven National Laboratory to Hos
Major New Nuclear Physics Facility

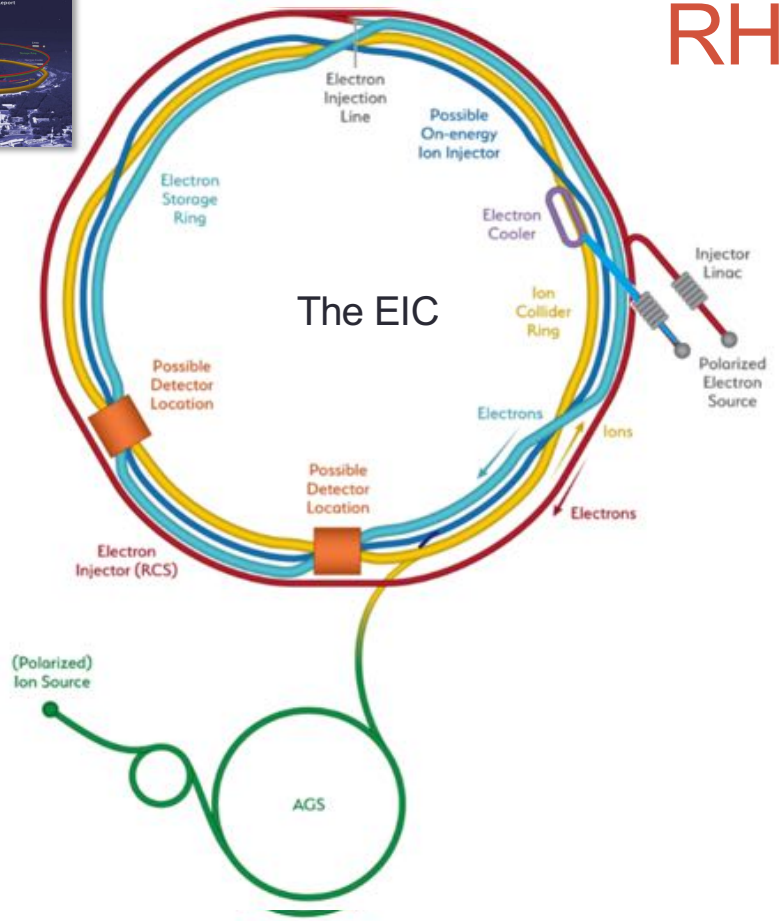
JANUARY 9, 2020

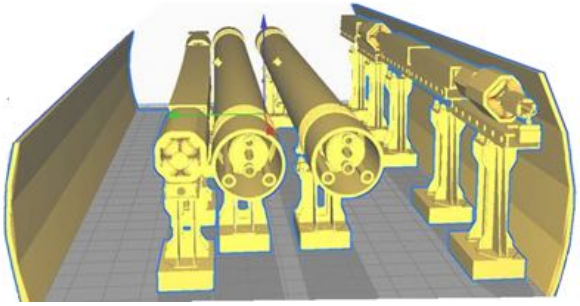
Home » U.S. Department of Energy Selects Brookhaven National Laboratory to Host Major New Nuclear Physics Facility

WASHINGTON, D.C. – Today, the **U.S. Department of Energy (DOE)** announced the selection of Brookhaven National Laboratory in Upton, NY, as the site for a planned major new nuclear physics research facility.



RHIC → EIC





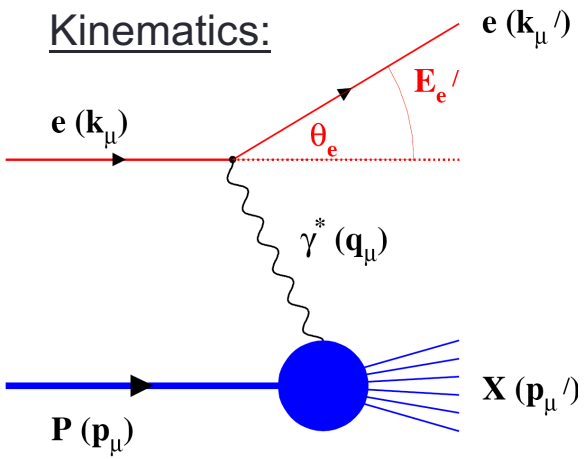
The strong hadron cooling facility completes the facility

- Hadron Storage Ring
- Electron Storage Ring
- Electron Injector Synchrotron
- Possible on-energy Hadron injector ring
- Hadron injector complex

The Science Of EIC

Deep Inelastic Scattering: Precision and control

Kinematics:



$$Q^2 = -q^2 = -(k_\mu - k'_\mu)^2$$

Measure of resolution power

$$Q^2 = 2E_e E'_e(1 - \cos\Theta_{e'})$$

$$y = \frac{pq}{pk} = 1 - \frac{E'_e}{E_e}\cos^2\left(\frac{\theta'_e}{2}\right)$$

Measure of inelasticity

$$s = 4\,E_t\,E_e$$

$$x = \frac{Q^2}{2pq} = \frac{Q^2}{sy}$$

Measure of momentum fraction of struck quark

Hadron :

$$z = \frac{E_h}{\nu};\ p_t$$

with respect to γ

High lumi & acceptance

Exclusive DIS

detect & identify *everything* e+p/A → e'+h(π,K,p,jet)+…

Semi-inclusive events:

e+p/A → e'+h(π,K,p,jet)+X

detect the scattered lepton in coincidence with identified hadrons/jets

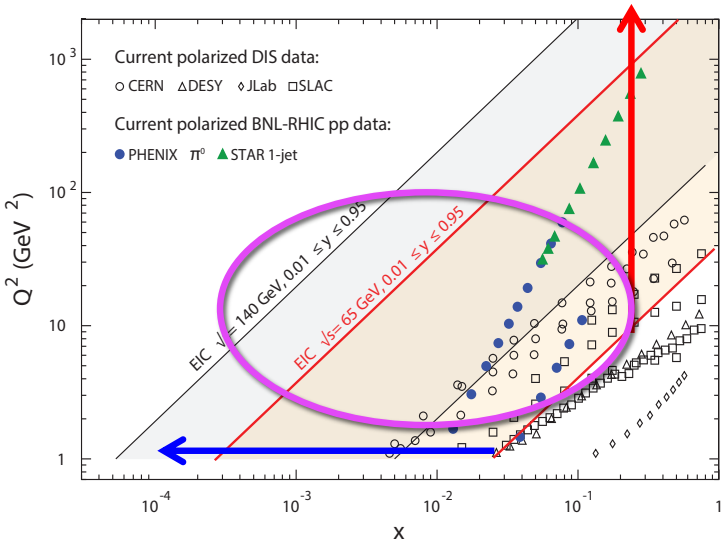
Inclusive events:

e+p/A → e'+X

detect *only the scattered lepton* in the detector

Low lumi & acceptance

EIC: Kinematic reach & properties

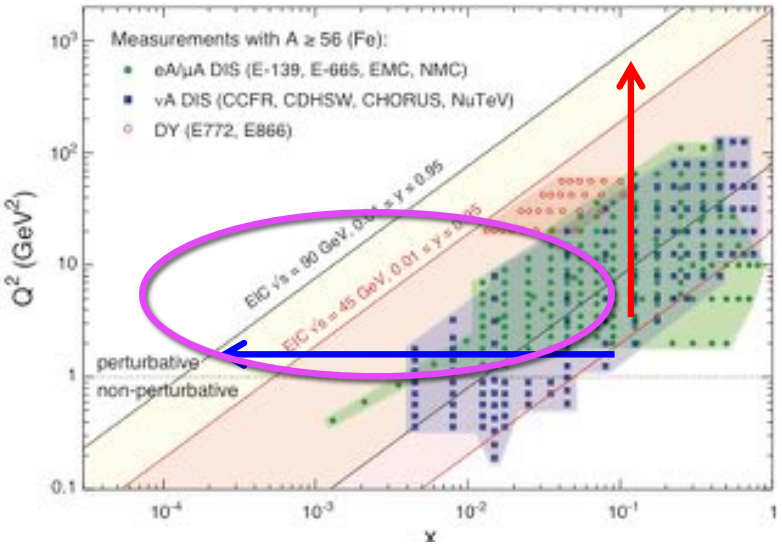


For e-N collisions at the EIC:

- ✓ **Polarized** beams: e, p, d/^{3}He
- ✓ Variable center of mass energy
- ✓ Wide Q^2 range → evolution
- ✓ Wide x range → spanning valence to low-x physics

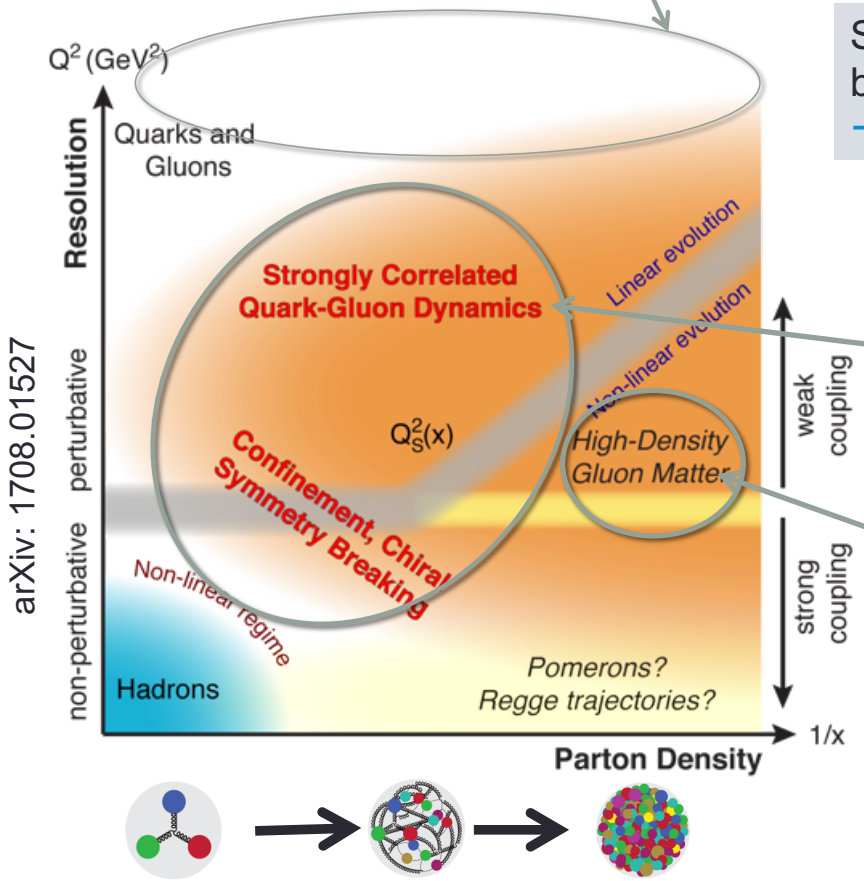
For e-A collisions at the EIC:

- ✓ **Wide range in nuclei**
- ✓ Luminosity per nucleon same as e-p
- ✓ Variable center of mass energy
- ✓ Wide x range (evolution)
- ✓ Wide x region (reach high gluon densities)



QCD Landscape to be explored by a future facility

QCD at high resolution (Q^2) —weakly correlated quarks and gluons are well-described



arXiv: 1708.01527

Strong QCD dynamics creates many-body correlations between quarks and gluons
→ hadron structure emerges

Systematically explore correlations in this region.

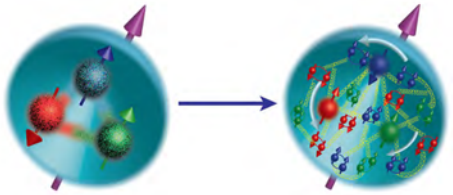
An exciting opportunity: Observation of a new regime in QCD of weakly coupled high-density matter

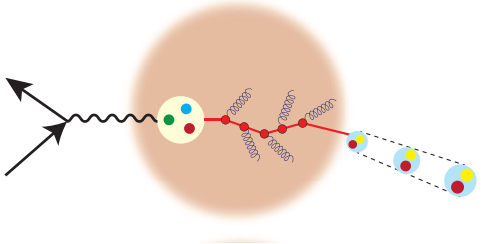
Need Precision and Control

A new facility is needed to investigate, with precision, the dynamics of gluons & sea quarks and their role in the structure of visible matter

How are the sea quarks and gluons, and their spins, distributed in space and momentum inside the nucleon?

How do the nucleon properties emerge from them and their interactions?





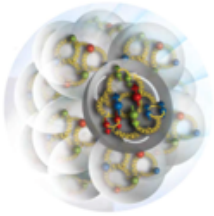
How do color-charged quarks and gluons, and colorless jets, interact with a nuclear medium?

How do the confined hadronic states emerge from these quarks and gluons?

How do the quark-gluon interactions create nuclear binding?

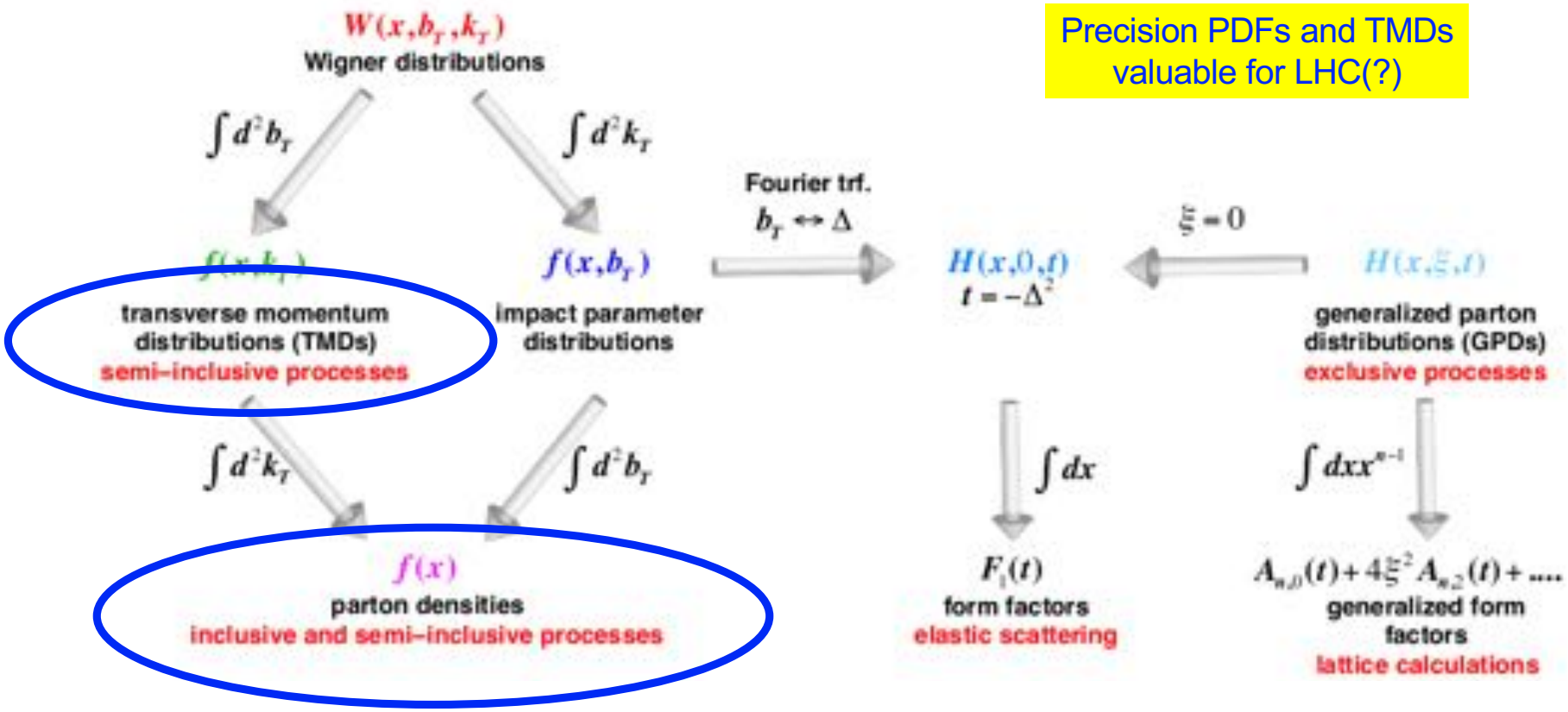
How does a dense nuclear environment affect the quarks and gluons, their correlations, and their interactions?

What happens to the gluon density in nuclei? Does it saturate at high energy, giving rise to a gluonic matter with universal properties in all nuclei, even the proton?



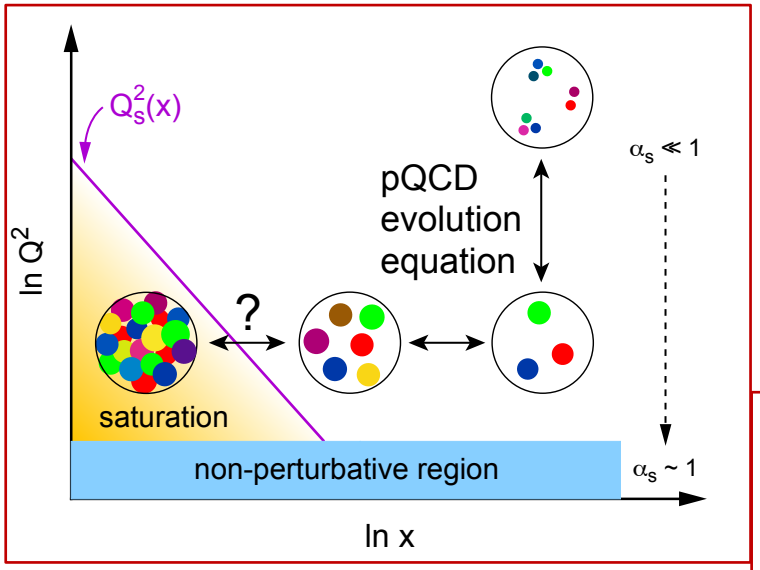
gluon emission ? = gluon recombination

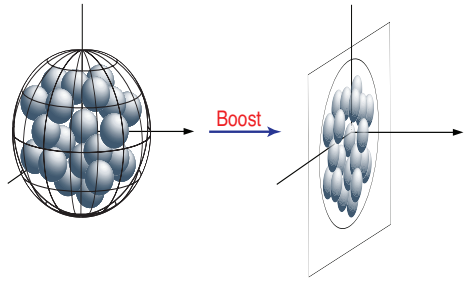
2+1D Imaging of hadrons: beyond precision PDFs and TMDs

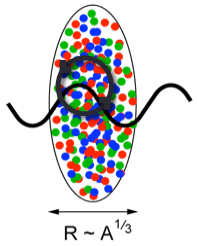


Precision PDFs and TMDs valuable for LHC(?)

Advantage of the nucleus over proton

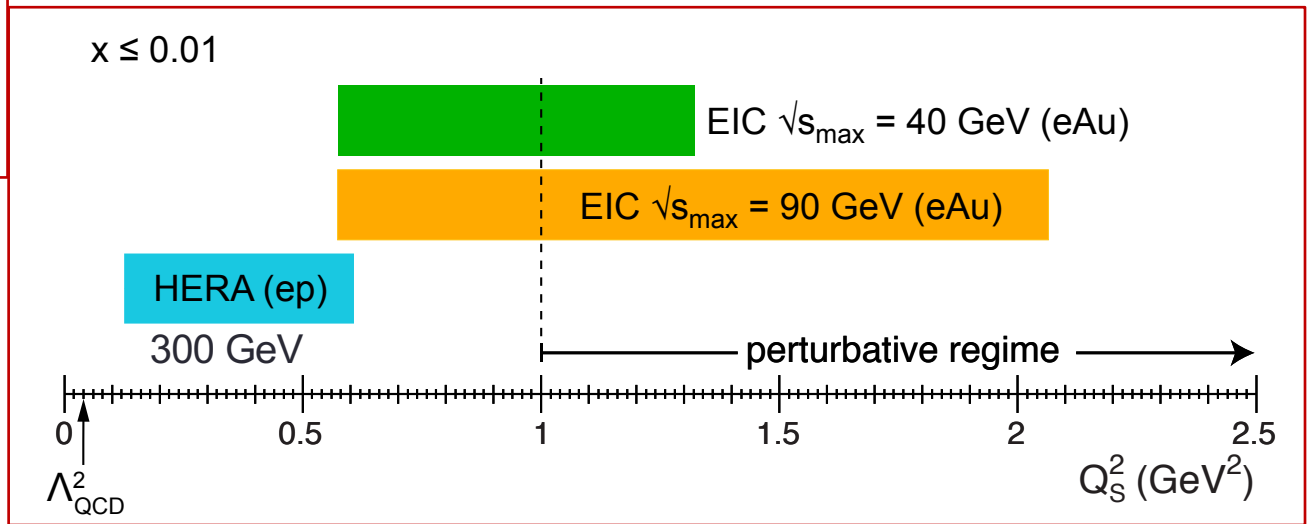






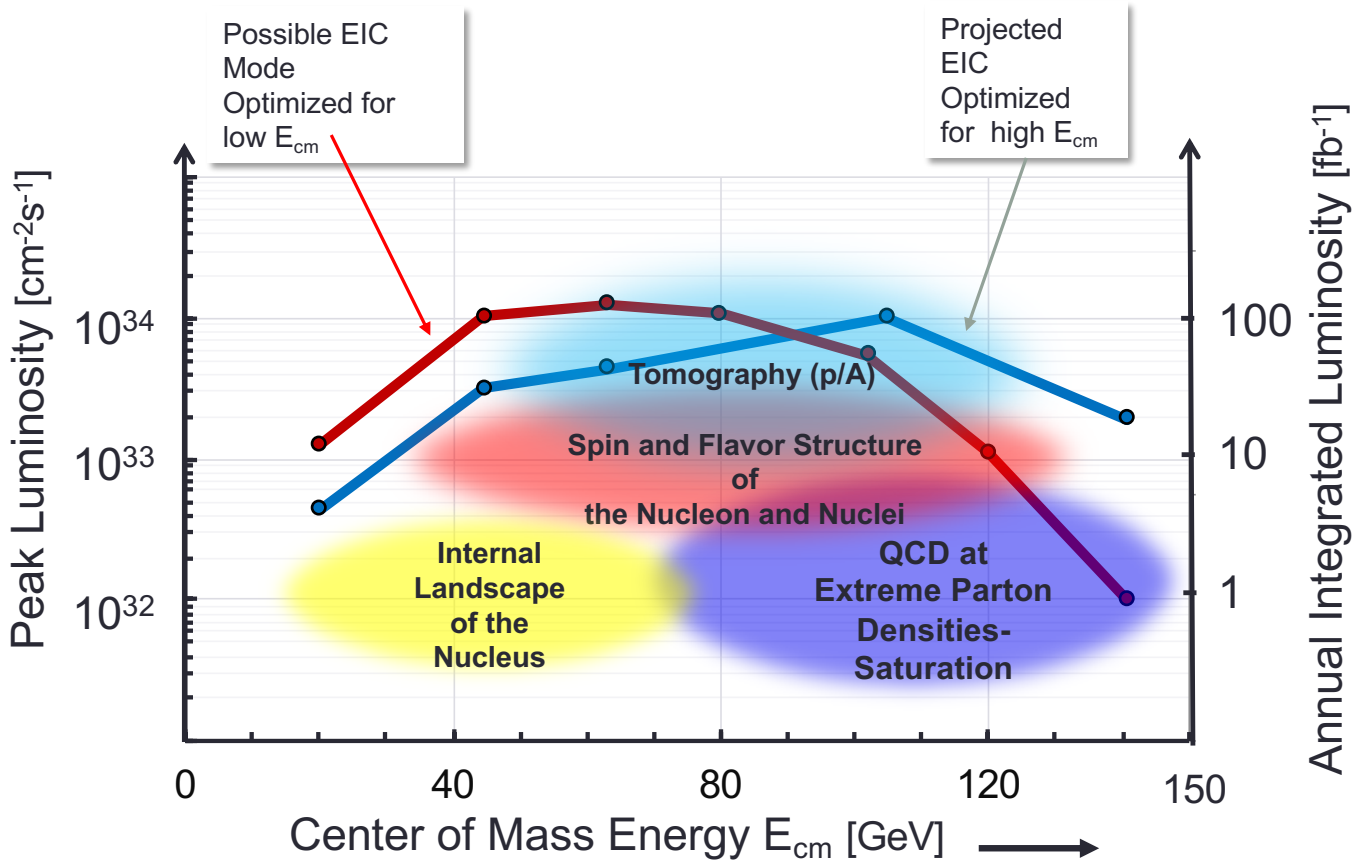
$$(Q_s^A)^2 \approx cQ_0^2 \left[\frac{A}{x}\right]^{1/3}$$

$L \sim (2m_N x)^{-1} > 2\ R_A \sim A^{1/3}$



Accessible range of saturation scale Q_s^2 at the EIC with e+A collisions.
arXiv:1708.01527

EIC Science : Luminosity vs. Center of Mass



Physics @ the US EIC beyond the EIC White Paper

Of HEP/LHC-HI interest to Snowmass 2021 (EF 05, 06, and 07 and possibly also EF 04)

New Studies with proton or neutron target:

- Impact of precision measurements of unpolarized PDFs at high x/Q^2, on LHC-Upgrade results(?)
- What role would TMDs in e-p play in W-Production at LHC? Gluon TMDs at low-x!
- Heavy quark and quarkonia (c, b quarks) studies with 100-1000 times lumi of HERA
- Does polarization of play a role (in all or many of these?)

Physics with nucleons and nuclear targets:

- Quark Exotica: 4,5,6 quark systems…? Much interest after recent LHCb led results.
- Physic of and with jets with EIC as a precision QCD machine:
  - Internal structure of jets
  - Studies with jets: Jet propagation in nuclei… energy loss in cold QCD medium
- Entanglement entropy & connection to fragmentation, hadronization, confinement
- Connection to p-A, d-A, A-A at RHIC and LHC
- Polarized light nuclei in the EIC

Precision electroweak and BSM physics:

- Electroweak physics & searches beyond the SM: Parity, charge symmetry, lepton flavor violation

Recent initiatives in precision QCD & EW/BSM Physics at the EIC

LPC Workshop on **Physics Connections between LHC & EIC**: November 13-15, 2019 at FNAL : Synergies between HEP and EIC/NP common interests

(A. Deshpande, T. Hobbs, J. Qiu, R. Yoshida, R. Boughezal, J. Campbell, O. Evdokimov, S. Hoeche, F. Petriello)

- Precision QCD, Monte Carlo event generators, lattice QCD, advance computing, opportunities in Electroweak sector & BSM searches

CFNS Workshop on Electroweak and BSM physics at the EIC: May 6-7, 2020

Revisited topics of interest in EW physics

(W. Deconick, Y. Ferlatova, C. Gal, M. Gericke)

- Relevant HERA precisions QCD studies & BSM Searches, LF & LN violation studies, Parity violating e-p scattering ($g_1^{\gamma Z}$, $g_5^{\gamma Z}$), Charge Symmetry Violation, Dark photon searches

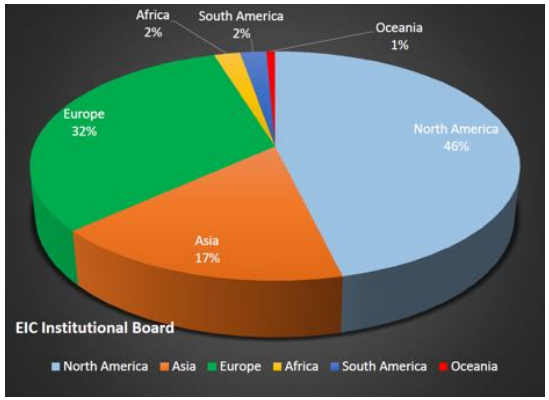
Yellow Reports for Detector Design(s)

Community led activity to come up with design concepts for detectors

Forming consortia for subsystems and evolve into collaborations

Coordinated by the EIC Users Group

The EIC Users Group: EICUG.ORG



Formally established in 2016
~1075+ Ph.D. Members from 31 countries, 224 institutions
New members welcome

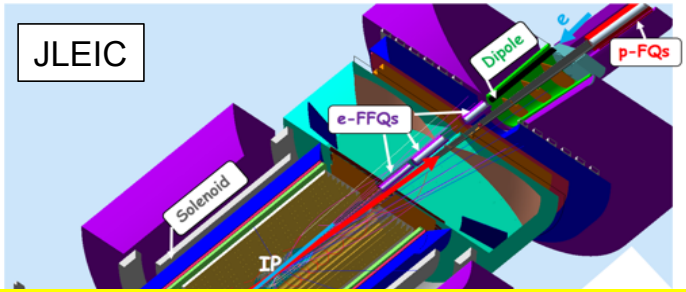
New:
Center for Frontiers in Nuclear Science (at Stony Brook/BNL)
EIC^2 at Jefferson Laboratory

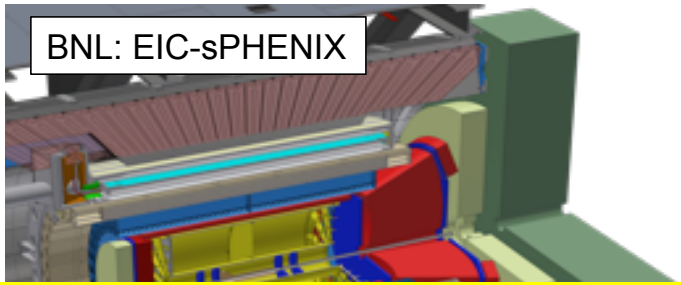
EICUG Structures in place and active:
EIC UG Steering Committee, Institutional Board, Speaker's Committee, Election & Nominations Committee
Task forces on:
-- Beam polarimetry, Luminosity measurement
-- Background studies, IR Design

Year long workshops: Yellow Reports for detector design

Annual meetings: Stony Brook (2014), Berkeley (2015), **ANL (2016), Trieste (2017), CAU (2018), Paris (2019), FIU (2020), Warsaw (2021)**

Current EIC detector



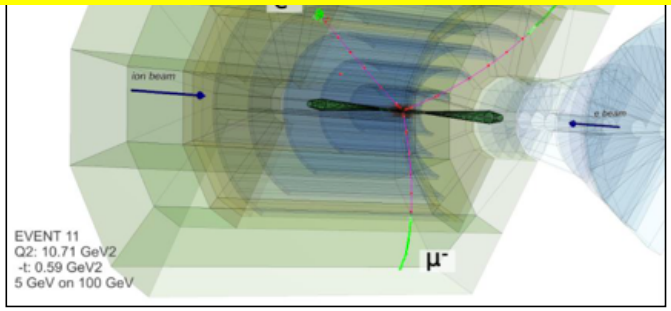


The EIC Users Group has just started a YELLOW REPORT writing activity that will help us move toward Technical Design Reports

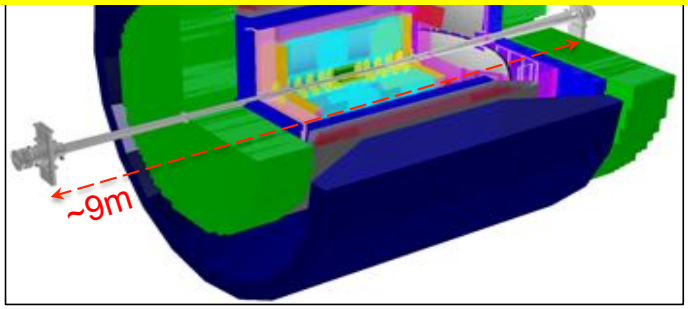
New ideas and members welcome to join this effort:
EICUG.ORG or contact me.

Defining features

Click here



Time OPtimized Silicon Detector for EIC



EICUG Led Yellow Report Preparation Activity

Intended to prepare a pre-Conceptual Design for an EIC detector by early 2021.

By 2023 (CD3) most of the technical and engineering design of the detector.

The Yellow Report Web Page for more details.

January 2020	Software tutorials are given, all activities are underway
March 19-21	First workshop at Temple University – Philadelphia *Goal: present progress for various groups and sub-groups, with much discussion and work time, initiate detector complementarity study based on detector technologies*
May 22-24	Second workshop at U of Pavia – Pavia, Italy *Goal: present initial physics measurements and detector requirements following five chosen processes/tools (inclusive measurements, semi-inclusive measurements, jets and heavy quarks, exclusive measurements, diffractive measurements & tagging), present detector concepts and implications for physics measurements. Complete detector requirements table including segmentation needs.*
August 3-7	Status reports at EICUGM @ FIU – Miami, FL *Goal: Conveners/sub-conveners inform community about status and progress. Conveners identify possible issues (if any) in meeting with EICUG Steering Committee.*
September 17-19	Third workshop at CUA – Washington, DC *Goal: present mature studies of detector requirements from physics processes, balance detector concepts versus impact on physics measurements. Discuss possible systematics reduction among complementary detector choices. Complete final "to-do" list for YR(s).*
November 19-21	Fourth workshop at UCB/LBL – Berkeley, CA or Final Meeting (assembly of Yellow Report(s)) *Goal: distribute draft YR sections before meeting*
January 2021	(optional) Final Meeting

Expression of Interest (EoI)

- Machine design allows for up to 2 detectors at the EIC
- Physics from EIC should start as soon as the machine is ready and starts operating
- How many detectors, what design should we have on Day 1? What should we plan for on day N, where N ~ 700-1000?

- Currently we have about 1100 EIC User Group members of which half (~600) are experimentalists (& a quarter each accelerator physicists and theorist).
- *The Users group is expected to grow but how much and with what technical means, experience and interest? This will critically determine how we plan our detector strategy.*

- Call for Expression of Interest (EoI), a non-binding information gathering campaign is being launched today (June 1st). ***Collect information and form strategy accordingly.***
- End of EoI period: End of November 2020.

- You are welcome to join this effort.

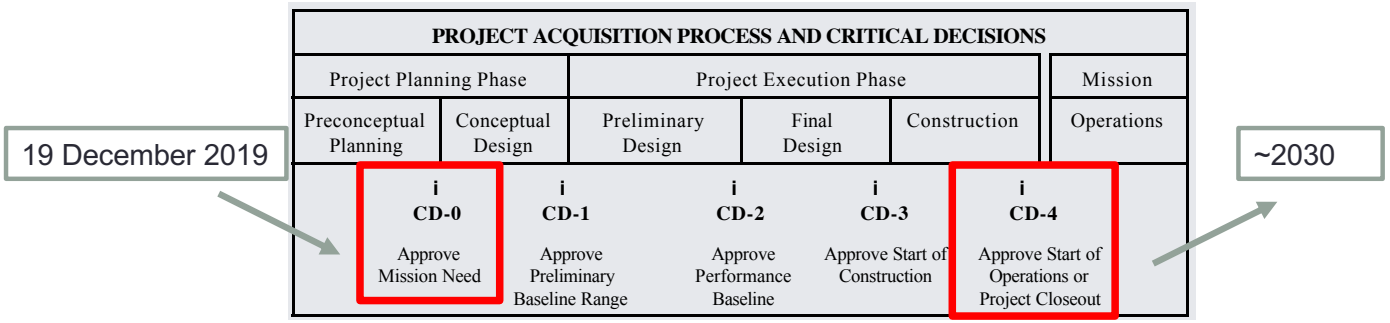
Summary & Outlook

- Electron Ion Collider, a high-energy **high-luminosity polarized e-p, e-A collider**, funded by the will be built in this decade and operate in the next.
  - **Up to two hermetic full acceptance detectors under consideration**
  - A non-binding Expression of Interest (EoI) request will inform the detector strategy
  - Community led detector design being developed through a Yellow Report Writing effort

- **Can EIC serve physics interests of the High Energy Physics Community?**
  - Opportunity for scientists from NP and HEP to collaborate and explore: High interest in the Snowmass 2021 participants of EF 05, 06 and 07 (may be more?)
  - EIC Users Group is organizing itself to prepare Yellow Reports for input to detector design TDRs.
  - **Snowmass 2021 timely to study potential synergies.**

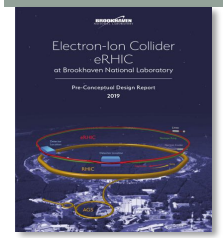
Thank you

Critical Decision Process

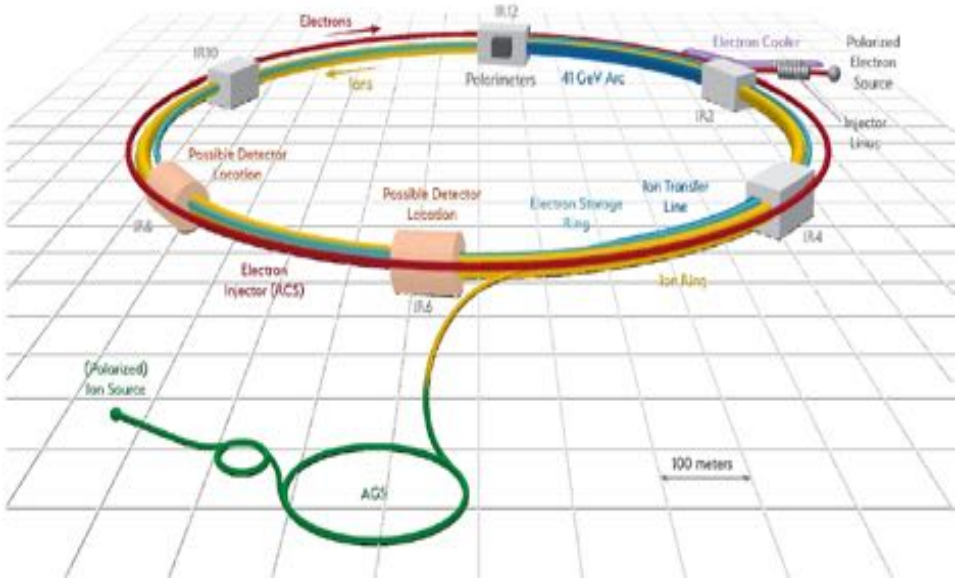


CD-0	CD-1	CD-2	CD-3	CD-4
Actions Authorized by Critical Decision Approval				
• Proceed with conceptual design using program funds • Request PED funding	• Allow expenditure of PED funds for design	• Establish baseline budget for construction • Continue design • Request construction funding	• Approve expenditure of funds for construction	• Allow start of operations or project closeout

PED: Project Engineering & Design



The US Electron Ion Collider



- Electron storage ring with frequent injection of fresh polarized electron bunches
- Hadron storage ring with strong cooling or frequent injection of hadron bunches

Hadrons up to 275 GeV

- Existing RHIC complex: Storage (Yellow), injectors (source, booster, AGS)
- Need few modifications
- RHIC beam parameters fairly close to those required for EIC@BNL

Electrons up to 18 GeV

- Storage ring, provides the range sqrt(s) = 20-140 GeV. Beam current limited by RF power of 10 MW
- Electron beam with variable spin pattern (s) accelerated in on-energy, spin transparent injector (Rapid-Cycling-Synchrotron) with 1-2 Hz cycle frequency
- Polarized e-source and a 400 MeV s-band injector LINAC in the existing tunnel

Design optimized to reach 10^{34} $cm^{-2}sec^{-1}$

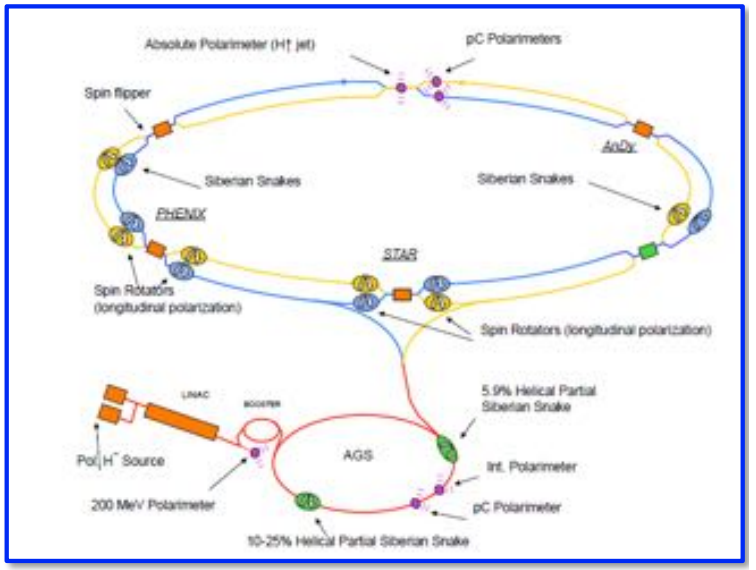
eRHIC Hadron Polarization

Measured RHIC Results:

- Proton Source Polarization 83 %
- Polarization at extraction from AGS 70%
- Polarization at RHIC collision energy 60%

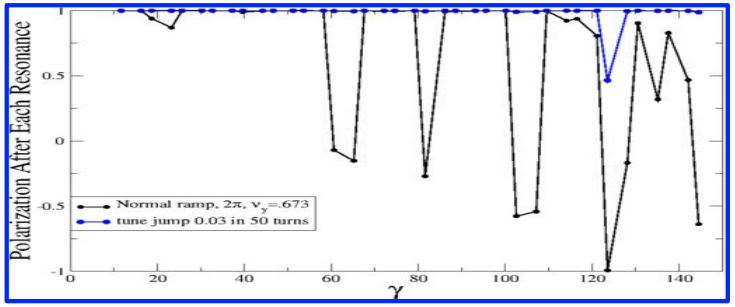
Planned near term improvements:

AGS: Stronger snake, skew quadrupoles, increased injection energy
➔expect 80% at extraction of AGS
RHIC: Add 2 snakes to 4 existing no/reduce polarization loss
➔ expect 80% in Polarization in RHIC and eRHIC
Expected simulations results benchmarked against RHIC operations



^{3}He in eRHIC with six snakes

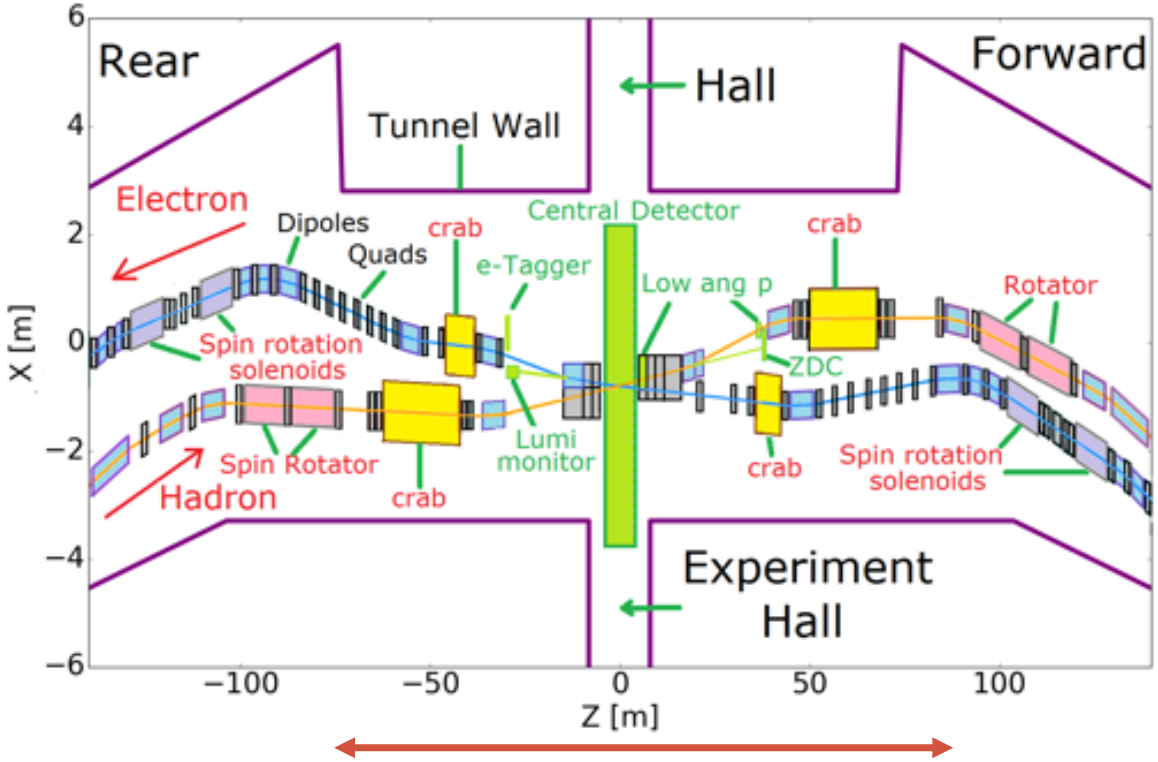
Achieved 85% polarization in 3He ion source
Polarization preserved with 6 snakes for up to twice the design emittance



Deuterons in eRHIC:

Requires tune jumps in the AGS, then
benchmarked simulation show 100% Spin transparency
No polarization **loss** expected in the eRHIC hadron ring

Full Acceptance EIC Interaction Region Layout



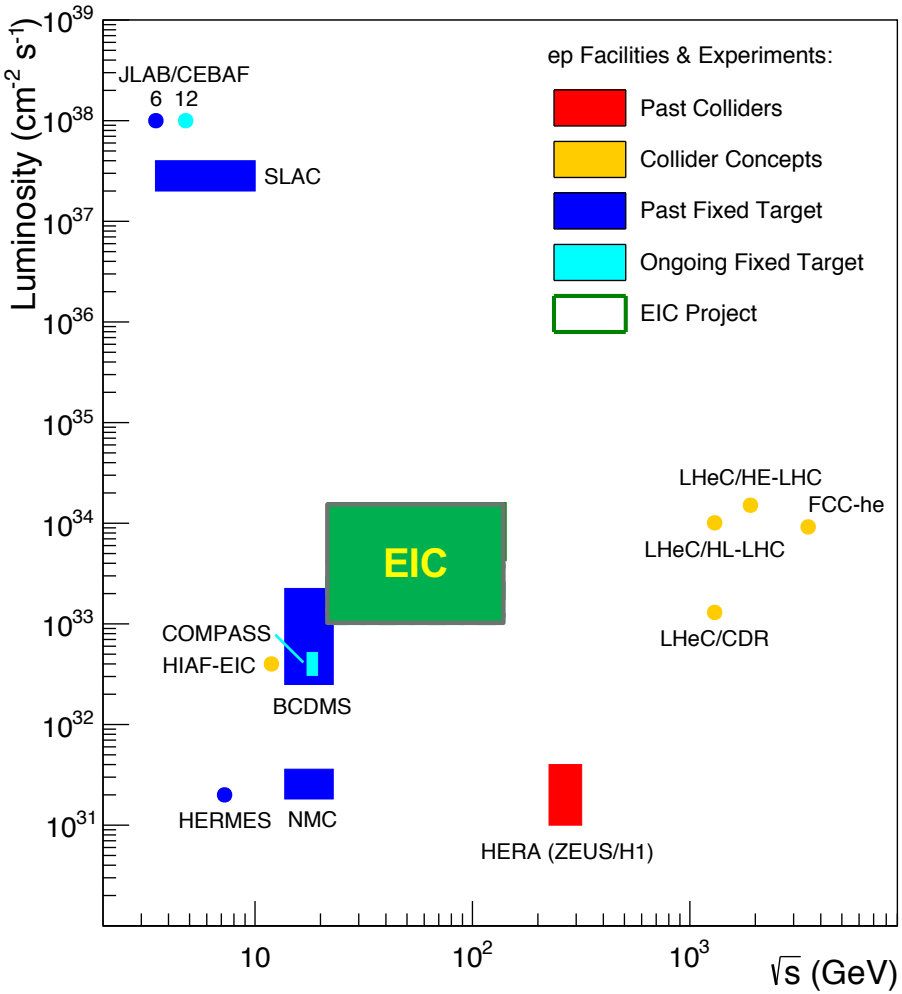
Detector Components
Far beyond the central detector

Design

- All superconducting magnets
  - ➢ Only 5 magnets need collared Nb-Ti coils
  - ➢ All other magnets can be built with **direct wind** of Nb-Ti wire
- Full acceptance e.g. P_t =200 MeV/c-1.3 GeV/c
  - ➢ Neutrons 4 mrad
- Large Aperture Dipole w/ instrumented gap
- Modest IR chromaticity
- Hadrons up to β<200m

➔ Manageable dynamic aperture optimization

Uniqueness of the US EIC among all DIS Facilities



All DIS facilities in the world.

However, if we ask for:

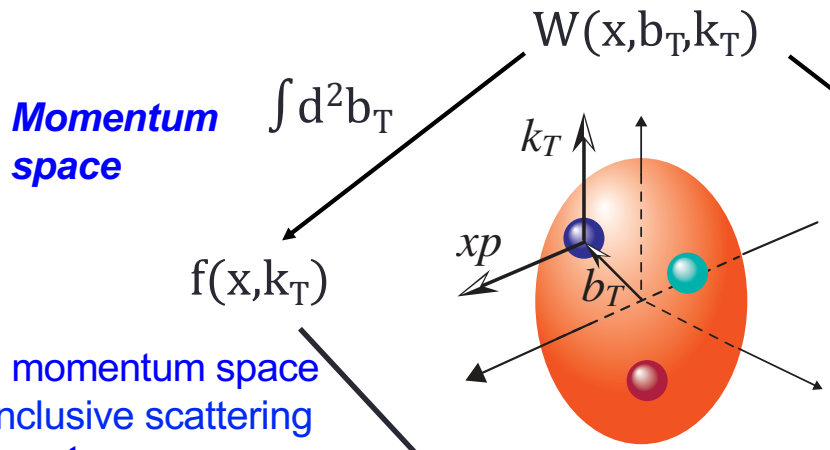
- high luminosity & **wide reach in √s**

No other facility has or plans for
- **polarized lepton & hadron beams**
- **nuclear beams**

EIC a truly unique facility

(1+2)-Dimensional Imaging Quarks and Gluons: in Protons

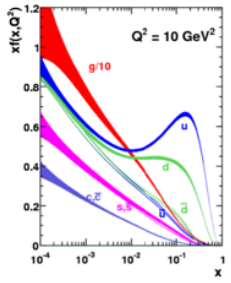
Wigner functions $W(x,b_T,k_T)$
offer unprecedented insight into confinement and chiral symmetry breaking.



Spin-dependent 3D momentum space images from semi-inclusive scattering → **Transverse Momentum Distribution**

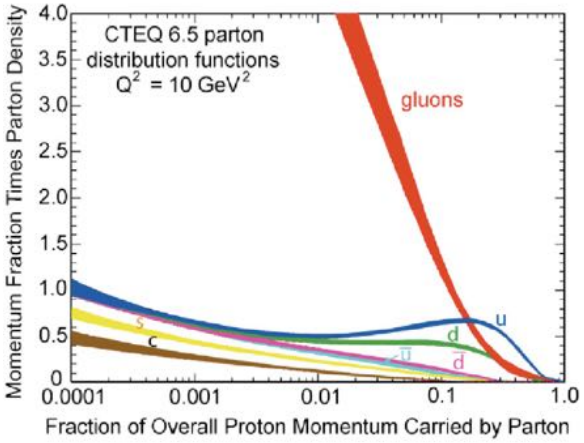
Spin-dependent 2D coordinate space (transverse) + 1D (longitudinal momentum) images from exclusive scattering (Deeply Virtual Compton Scattering and Deeply Virtual Vector Meson production) → **Generalized Parton Distributions**

Precision PDFs and TMDs for HEP?



10-100 times more precise PDFs

Position and momentum → Orbital motion of quarks and gluons



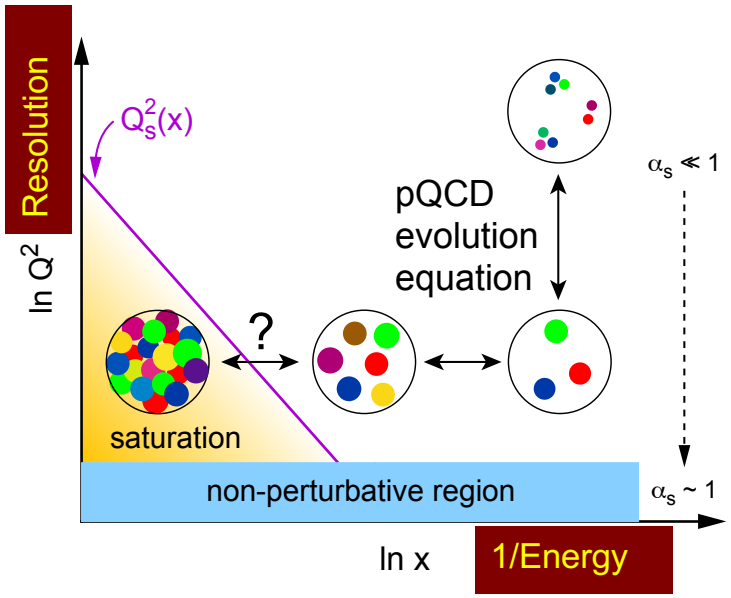
What do we learn from low-x studies?

What tames the low-x rise?

- New evolution eqn.s @ low x & moderate Q^2
- Saturation Scale $Q_S(x)$ where gluon emission and recombination comparable

gluon emission = gluon recombination

At Q_S



First observation of gluon recombination in nuclei:
➔leading to a *collective* gluonic system!
Study: *different* nuclei ➔ a universal property?
→ Color Glass Condensate correct effective theory?
➔ Initial State in Heavy Ion Collisions

Yellow Reports Conveners

- Kick-off Meeting @ MIT 12-13 December 2019
  - https://www.jlab.org/indico/event/348/
- Physics Conveners:
  - Adrian Dumitru (Baruch)
  - Olga Evdokimov (University of Illinois at Chicago)
  - Andreas Metz (Temple)
  - Carlos Muñoz Camacho (Orsay)
- Detector Conveners:
  - Ken Barish (UC Riverside)
  - Tanja Horn (CUA)
  - Peter Jones (Birmingham)
  - Silvia Dalla Torre (Trieste)
  - Markus Diefenthaler, ex-officio (JLab)

Other YR meetings:

March 2020 (Temple U)

May 2020 (Pavia)

July/August 2020 (FIU)

September 2020 (CUA)

November 2020 (LBNL)

If needed January-March 2021

Physics Working Group Sub-conveners

Inclusive

Theory: Nobuo Sato (JLab)
Experiment: Renee Fatemi (Kentucky), Barak Schmookler (Stony Brook)

Semi-Inclusive DIS

Theory: Bowen Xiao (CCNU, China), Alexey Vladimirov (Regensburg)
Experiment: Anselm Vossen (Duke), Ralf Seidl (RIKEN), Justin Stevens (W&M)

Jets, heavy quarks

Theory: Ivan Vitev (LANL), Frank Petriello (Argonne & Northwestern U.)
Experiment: Ernst Sichtermann (LBL), Brian Page (BNL), Leticia Mendez (ORNL)

Exclusive

Theory: Tuomas Lappi (Jyvaskyla), Barbara Pasquini (Pavia)
Experiment: Raphaël Dupré (Orsay), Salvatore Fazio (BNL), Daria Sokhan (Glasgow)

Diffractive & Tagging

Theory: Wim Cosyn (Florida), Anna Stasto (PSU)
Experiment: Or Hen (MIT), Douglas Higinbotham (JLab), Spencer Klein (LBNL)

Detector Working Group Sub-conveners

- **Tracking (including vertexing),** Conveners: Kondo Gnanvo (UVA), Leo Greiner (LBNL), Annalisa Mastroserio (INFN)
- **Particle ID**, Conveners: Tom Hemmick (SBU), Patrizia Rossi (JLab)
- **Calorimetry (EM and Hadronic),** Conveners: Vladimir Berdnikov (CUA), Eugene Chudakov (JLab)
- **Far-Forward Detectors**, Conveners: Alexander Jentsch (BNL), Michael Murray (Kansas)
- **DAQ/Electronics**, Conveners: Andrea Celentano (INFN), Damien Neyret (CEA Saclay)
- **Polarimetry/Ancillary Detectors:** Conveners: Elke Aschenauer, Dave Gaskell
- **Central Detector/Integration & Magnet,** Conveners: Alexander Kiselev (BNL), TBA
- **Forward Detector/IR Integration,** Convener: Yulia Furletova (JLab)
- **Infrastructure and Installation,** Convener: TBA
- **Detector Complementarity,** Conveners: Elke Aschenauer (BNL), TBA
- **Simulations,** Convener: Markus Diefenthaler (JLAB)

See http://www.eicug.org/web/content/yr-detector-working-group for updates.

EIC Software Working Group

https://software.eicug.org/
https://eic.gitlab.io/documents/quickstart/

The software group has used Docker to make installation very easy!

Install Docker
Install EIC Software via Docker (includes GEANT4, ROOT, Python, …)
Launch the tutorial and start running the software!

And if you learn like my kids, you can watch the YouTube video tutorials:

https://www.youtube.com/channel/UCXc9WfDKdlLXoZMGrotkf7w

Yellow Report Physics Topics

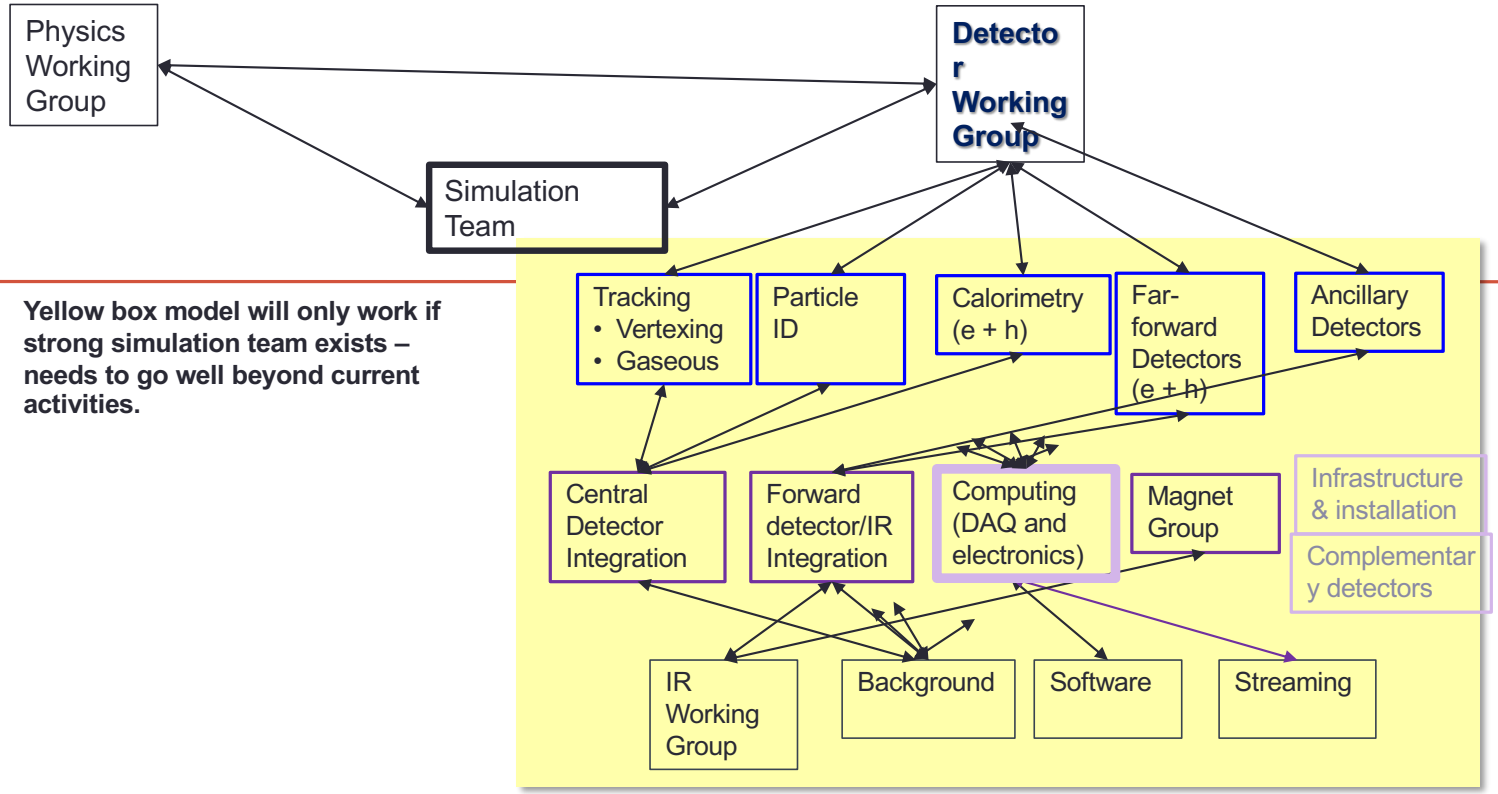
1. **Global properties and parton structure of hadrons**
   a. Spin structure of proton & neutron (spin sum rule, helicity distributions, transversity)
   b. Mass of the nucleon and mesons
   c. Multi-parton correlations (structure function g_2)
   d. (Inclusive) diffraction
   e. **Precision unpolarized PDFs**

2. **Multi-dimensional imaging of hadrons**
   a. GPDs and 3D-imaging (includes also Ji's sum rule, pressure and shear distributions)
   b. TMDs and 3D-imaging
   c. Wigner functions (includes, in particular, orbital angular momentum)
   d. Form factors and 2D-imaging in position space

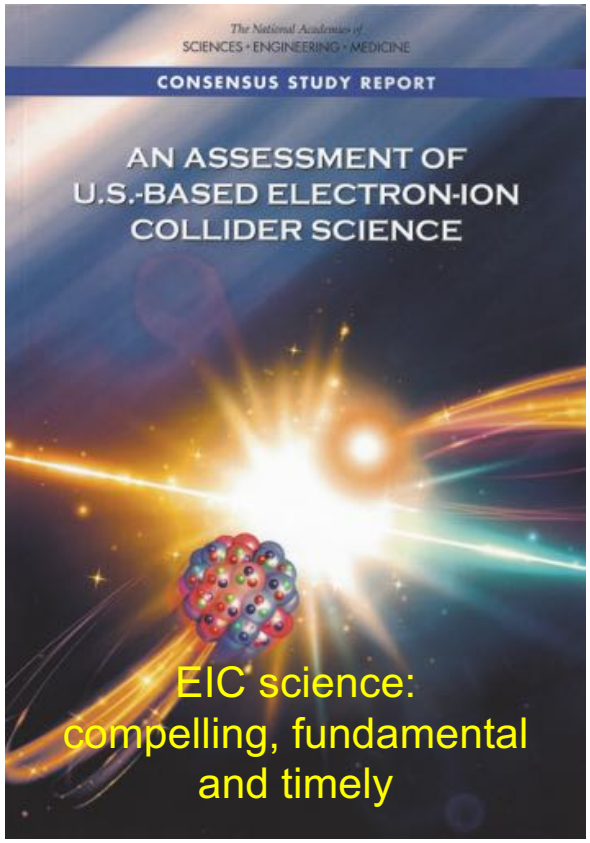
3. **The Nucleus: A Laboratory for QCD**
    a. High parton densities and Saturation
    b. Diffraction
    c. Particle propagation through matter, energy loss
    d. Collective effects (shadowing, anti-shadowing, ridge effect, other emergent phenomena)
    e. Special opportunities with jets and heavy quarks
    f. Short-range correlations, origin of nuclear force
    g. Structure of light (polarized) nuclei

4. **Understanding hadronization (using protons & nuclei)**
    a. Hadronization in the nuclear environment
    b. Hadronization in the vacuum
    c. Particle production for identified hadron species
    d. Production mechanism for quarkonia and exotic states
    e. Spectroscopy

Organogram



Yellow box model will only work if strong simulation team exists – needs to go well beyond current activities.



Consensus Study Report on the US based Electron Ion Collider

Summary:

The science questions that an EIC will answer *are central* to completing an understanding of atoms as well as being integral to the agenda of nuclear physics today. In addition, the development of an EIC would *advance accelerator science and technology* in nuclear science; it would as well *benefit other fields of accelerator based science and society*, from medicine through materials science to elementary particle physics